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Detecting heavy charged Higgs bosons at the LHC with triple b -tagging

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Abstract

We investigate the charged Higgs boson signal at the LHC using its dominant production and decay modes with triple b -tagging, i.e. $tH^- \rightarrow t\bar{t}b \rightarrow b\bar{b}bW^+W^-$, followed by leptonic decay of one W and hadronic decay of the other. We consider the continuum background from the associated production of $t\bar{t}$ with a b - or a light quark or gluon jet, which can be mis-tagged as b -jet. We reconstruct the top quark masses to identify the 3rd b -jet accompanying the $t\bar{t}$ pair, and use its p_T distribution to distinguish the signal from the background. Combining this with the reconstruction of the H^\pm mass gives a viable signature over two interesting regions of the parameter space – i.e. $\tan\beta \sim 1$ and $\sim m_t/m_b$.

The Minimal Supersymmetric Standard Model (MSSM) contains two complex Higgs doublets, ϕ_1 and ϕ_2 , corresponding to eight scalar states. Three of these are absorbed as Goldstone bosons leaving five physical states – the two neutral scalars (h^0, H^0), a pseudo-scalar (A^0) and a pair of charged Higgs bosons (H^\pm). All the tree-level masses and couplings of these particles are given in terms of two parameters, M_{H^\pm} and $\tan\beta$, the latter representing the ratio of the vacuum expectation values of ϕ_1 and ϕ_2 [1]. While any one of the above neutral Higgs bosons may be hard to distinguish from that of the Standard Model, the H^\pm carries a distinctive signature of the Supersymmetric (SUSY) Higgs sector. Moreover the couplings of the H^\pm are uniquely related to $\tan\beta$, since the physical charged Higgs boson corresponds to the combination

$$H^\pm = -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta. \quad (1)$$

Therefore the detection of H^\pm and measurement of its mass and couplings are expected to play a very important role in probing the SUSY Higgs sector.

Unfortunately it is very hard to extend the H^\pm search beyond the top quark mass at the Large Hadron Collider (LHC), because in this case the combination of dominant production and decay channels, $tH^- \rightarrow t\bar{t}b$, suffers from a large QCD background. The viability of a H^\pm signal in this channel had been investigated in [2,3] assuming triple b -tagging. Recently it was shown that with four b -tags one can get a better signal/background ratio, but at the cost of a smaller signal size [4]. Similar conclusions were also found for the H^\pm signal in its τ decay channel [5]. The charged Higgs boson signal at the LHC has also been investigated recently in subdominant production channels, $H^\pm W^\mp$ [6] and $H^\pm H^\mp$ [7], as well as the subdominant decay mode $H^\pm \rightarrow W^\pm h^0$ [8]. But it turns out to be at best marginal in each of these cases.

It is clear from the above discussion that the largest size of the H^\pm signal is expected to come from its dominant production and decay channels with triple b -tagging. The purpose of this paper is to reinvestigate the H^\pm signal in this channel in the light of the theoretical and experimental developments since the last analyses [2,3]. Several distinctions of the present study in comparison with those earlier ones are worth mentioning here.

- i) The signal cross-section was calculated in [2] and [3] using the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes respectively, i.e.

$$gb \rightarrow tH^- + \text{h.c.}, \quad (2)$$

and

$$gg \rightarrow t\bar{t}H^- + \text{h.c.}, \quad (3)$$

followed by the $H^- \rightarrow t\bar{t}b$ decay. Here we shall instead combine the two cross-sections and subtract out the overlapping piece to avoid double counting, as suggested in [9,10].

- ii) We shall use the p_T distribution of the 3rd b -tagged jet, accompanying the $t\bar{t}$ pair, for a better separation of the signal from the background.
- iii) The actual value of top quark mass (175 GeV) will be used here instead of the illustrative values used in [2,3].

- iv) Besides we shall be using current estimates of the b -tagging efficiency and rapidity coverage for the LHC [11] along with more recent structure functions [12,13].

The cross-section for the $2 \rightarrow 2$ process (2) is simple to calculate, while analytic expressions for the $2 \rightarrow 3$ processes (3) can be found in [4]. The resulting signal cross-sections shall be obtained by convoluting these partonic cross-sections with the MRS-LO(05A) parton densities [12]. We have also checked that essentially identical results are obtained with the CTEQ4L parton densities [13]. It may be noted here that both these cross-sections are controlled by the Yukawa coupling of the tbH vertex,

$$\frac{g}{\sqrt{2}M_W}H^+ [\cot \beta m_t \bar{t}b_L + \tan \beta m_b \bar{t}b_R] + \text{h.c.} \quad (4)$$

Consequently one gets fairly large values of the signal cross-section at the two ends of the MSSM allowed region,

$$\tan \beta \sim 1 \text{ and } \tan \beta \sim m_t/m_b, \quad (5)$$

with a pronounced minimum at $\tan \beta = \sqrt{m_t/m_b}$.

The question of overlap between the two H^\pm production processes (2) and (3) has been recently discussed in [9,10]. The b -quark in (2) comes from a gluon in the proton beam splitting into a collinear $b\bar{b}$ pair, resulting in a large factor of $\alpha_S \log(Q/m_b)$, where the factorisation scale is

$$Q \simeq m_t + M_{H^\pm}. \quad (6)$$

This factor is then resummed to all orders, $\alpha_S^n \log^n(Q/m_b)$, in evaluating the phenomenological b -quark structure function [14,15]. The 1st order contribution to the structure function is given by the perturbative solution to the DGLAP equation,

$$b'(x, Q) = \frac{\alpha_S}{\pi} \log\left(\frac{Q}{m_b}\right) \int_x^1 \frac{dy}{y} P_{gb}\left(\frac{x}{y}\right) g(y, Q), \quad (7)$$

where $P_{gb}(z) = (z^2 + (1-z)^2)/2$ is the gluon splitting function. The resulting contribution to $gb \rightarrow tH^-$ is already accounted for by $gg \rightarrow t\bar{b}H^-$ in the collinear limit. Thus while combining (2) and (3), the above contribution should be subtracted from the former to avoid double counting.

Fig. 1 shows the cross-sections for (2) and (3) at the LHC energy (14 TeV) against the H^\pm mass at $\tan \beta = 40$, using $m_b = 4.5$ GeV. It also shows their combined value, after subtracting out the gb' contribution from the former. While the cross-section for (2) is 2–3 times larger than that for (3), the bulk of the former is accounted for by the gb' contribution. Hence the combined cross-section is larger than that of (3) by only a factor of about 1.6. We also have checked that detection efficiencies for the processes (2) and (3) are very similar, since the extra b -jet in the latter case is relatively soft (missing the $p_T > 30$ selection cut discussed below over 70% of the time). We shall therefore simply multiply the cross-section for the $2 \rightarrow 3$ process (3) by the above mentioned factor of 1.6 in presenting the signal cross-sections.

It should also be mentioned here that the electroweak loop corrections to the tbH vertex (4) have been estimated to give up to 20% reduction in the signal cross-section depending

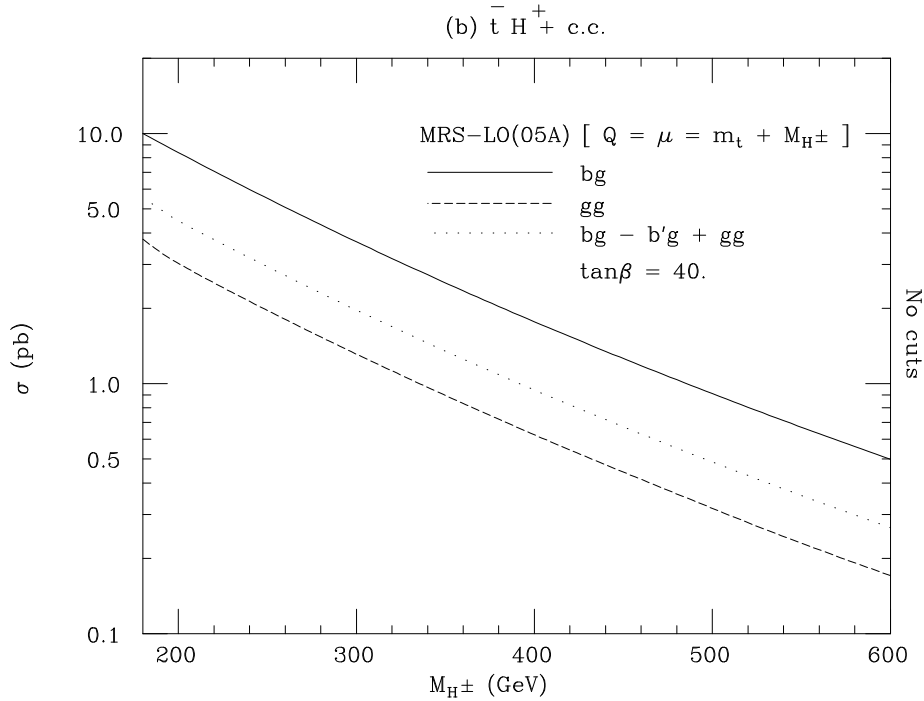


Figure 1: Cross section of the $2 \rightarrow 2$ process $gb \rightarrow tH^-$ (2), of the $2 \rightarrow 3$ one $gg \rightarrow \bar{t}bH^-$ (3) and of their sum after the subtraction of the gb' contribution, see eq. (7), for $\tan\beta = 40$ (including the charged conjugated final states). The PDF set used was MRS-LO(05A) with renormalisation and factorisation scales set equal to $m_t + M_{H^\pm}$. Normalisation is to the total cross sections without any branching ratios.

on M_{H^\pm} and $\tan\beta$ [16]. The corresponding QCD corrections are expected to be larger, but not yet available. Note that higher-order QCD effects in the $H^- \rightarrow \bar{t}b$ decay are easily accounted for by using the running value of the b mass, $m_b(M_{H^\pm})$, in the tbH coupling. We shall therefore use it in estimating the $H^- \rightarrow \bar{t}b$ decay rate. (Of course this has no significant impact on the signal since this branching fraction amounts to $\gtrsim 80\%$ over most of the parameter space of our interest.) The effects of SUSY QCD corrections may be larger, depending on the SUSY parameters [17]. We shall neglect this by assuming a large SUSY mass scale ~ 1 TeV.

The final state resulting from the above $2 \rightarrow 2$ ($2 \rightarrow 3$) signal process is

$$tH^-(\bar{b}) \rightarrow t\bar{t}b(\bar{b}) \rightarrow b\bar{b}b(\bar{b})W^+W^-. \quad (8)$$

We shall require leptonic decay of one W and hadronic decay of the other, resulting in a final state of

$$b\bar{b}b(\bar{b})\ell\nu q\bar{q}. \quad (9)$$

The hard lepton (e, μ) will be required for triggering and suppression of multi-jet background, while the presence of only one ν will enable us to do mass reconstruction. As mentioned earlier, the extra b -quark coming from the $2 \rightarrow 3$ process (3) is expected to be too soft to

pass our selection cuts or be tagged with a reasonable efficiency. We shall therefore require a minimum of 3 b -tagged and 2 untagged jets along with a lepton and a missing- p_T (\cancel{p}_T).

We shall consider the background to the final state (9) coming from

$$gb \rightarrow t\bar{t}b \rightarrow b\bar{b}bW^+W^-, \quad (10)$$

$$gg, q\bar{q} \rightarrow t\bar{t}g^* \rightarrow b\bar{b}b\bar{b}W^+W^-, \quad (11)$$

along with those from

$$\begin{aligned} gg, q\bar{q} &\rightarrow t\bar{t}g \rightarrow b\bar{b}gW^+W^-, \\ gq &\rightarrow t\bar{t}q \rightarrow b\bar{b}qW^+W^-, \end{aligned} \quad (12)$$

where the gluon or light quark jet (j) is mis-tagged as a b -jet. In fact (12) will turn out to be the largest background. The cross-sections for processes (10)–(12) are computed using MadGraph and HELAS [18,19].

Our analysis is based on simply a parton level Monte Carlo program. However we have tried to simulate detector resolution by a Gaussian smearing of all jet momenta with [2]

$$(\sigma(p_T)/p_T)^2 = (0.6/\sqrt{p_T})^2 + (0.04)^2, \quad (13)$$

and the lepton momentum with

$$(\sigma(p_T)/p_T)^2 = (0.12/\sqrt{p_T})^2 + (0.01)^2. \quad (14)$$

The \cancel{p}_T is obtained by vector addition of all the p_T 's after resolution smearing.

As a basic set of selection cuts we require

$$p_T > 30 \text{ GeV} \quad \text{and} \quad |\eta| < 2.5 \quad (15)$$

for all the jets and the lepton, where η denotes pseudorapidity and the p_T -cut is applied to the \cancel{p}_T as well. We also require a minimum separation of (ϕ is the azimuthal angle)

$$\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} > 0.4 \quad (16)$$

between the lepton and the jets as well as each pair of jets.

To improve the signal/background ratio and to estimate the H^\pm mass we follow a strategy similar to that in [2], except for the step (e) below, which is new.

- (a) The invariant mass of two untagged jets is required be consistent with $M_W \pm 15 \text{ GeV}$.
- (b) The neutrino momentum is reconstructed by equating p_ν^T with \cancel{p}_T and fixing p_ν^L within a quadratic ambiguity via $m(\ell\nu) = M_W$.
- (c) The invariant mass of the above untagged jet pair with one of the 3 b -tagged jets is required to be consistent with $m_t \pm 25 \text{ GeV}$. If several b -tagged jets satisfy this, the one giving the best agreement with m_t is selected.

- (d) The invariant mass of the ℓ and ν with one of the 2 remaining b -jets is required to be consistent with $m_t \pm 25$ GeV. In case of several combinations satisfying this, the one giving best agreement with m_t is selected along with the corresponding b -jet and p_ν^L .
- (e) The remaining (3rd) b -jet is the one accompanying the $t\bar{t}$ pair in the signal (8) or in the backgrounds (10)–(12)¹. For the signal it mainly comes from the $H^- \rightarrow \bar{t}b$ decay and is therefore quite hard, while it is expected to be very soft for the background processes. Hence the p_T -distribution of this b -jet shall be used to improve the signal/background ratio.
- (f) Finally we combine each of the top (anti)quarks in the reconstructed $t\bar{t}$ pair with the 3rd b -jet. Thus we obtain 2 entries per event in the M_{bt} invariant mass plot, one of which would correspond to the H^\pm mass peak for the signal.

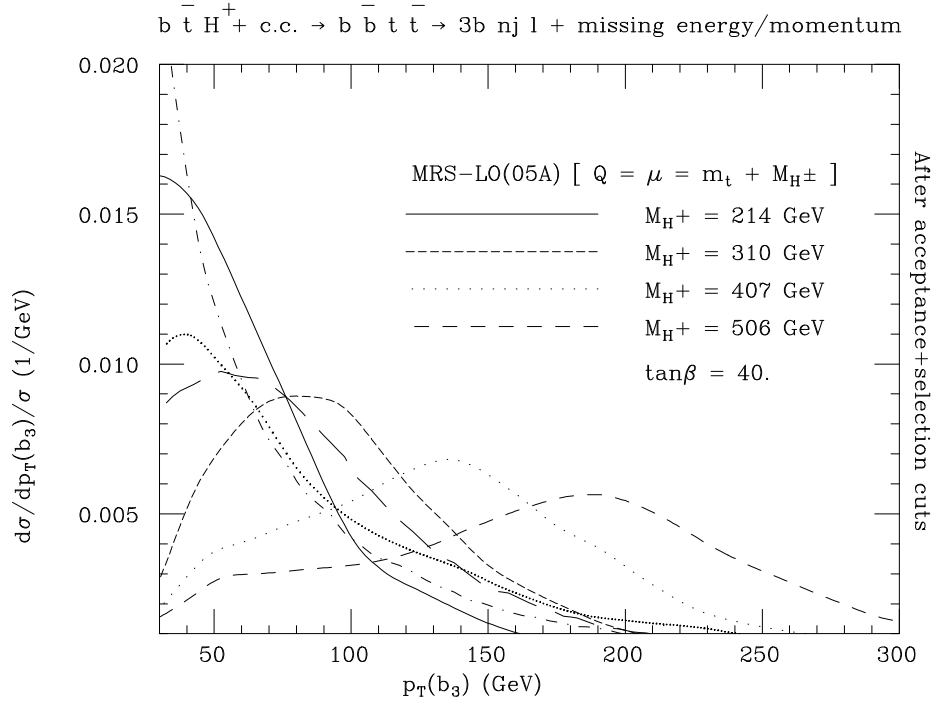


Figure 2: Differential distributions in transverse momentum of the b -quark accompanying the reconstructed $t\bar{t}$ pair in the signal (2)–(3), for four selected values of M_{H^\pm} in the heavy mass range, with $\tan\beta = 40$, after the acceptance and selection cuts described in the text: i.e. eqs. (15)–(16) and steps (a)–(d). The PDF set used was MRS-LO(05A) with renormalisation and factorisation scales set equal to $m_t + M_{H^\pm}$. The (fine-dotted)[long-dashed]{dot-dashed} curve represents the shape of the background process ((10))[(11)]{(12)}. Normalisation is to unity.

¹In case of a 4th b -jet surviving the $p_T > 30$ GeV cut the harder of the two b -jets accompanying the $t\bar{t}$ pair is selected.

Fig. 2 shows the p_T distribution of the 3rd b -jet accompanying the reconstructed $t\bar{t}$ pair as discussed above in step (e). We clearly see a harder p_T distribution for the signal compared to the background processes for a H^\pm mass ≥ 300 GeV. Thus we can improve the signal/background ratio over this mass range by imposing a

$$p_T > 80 \text{ GeV} \quad (17)$$

cut on this 3rd b -jet.

The top of Fig. 3 shows the signal cross-section along with those of the background processes (10)–(12) after applying the selection cuts (15)–(16) and the mass constraints of steps (a)–(d). No b -tagging efficiency or rejection factor has been applied yet. The effect of imposing the p_T -cut (17) on the 3rd b -jet is presented in the bottom plot. It is clearly shown to suppress the backgrounds significantly: in particular the dominant one from ttj (12) is reduced by a factor of 2.5 or so. In contrast the signal cross-section is essentially unaffected for a H^\pm mass ≥ 400 GeV.

Finally, Fig. 4 shows the signal and background cross-sections against the reconstructed bt invariant mass as discussed in step (f). Here we have included a b -tagging efficiency of 40% and a probability of 1% for mis-tagging a light quark or gluon jet (j) as b -jet [11]. The top figure shows the signal and background cross-sections separately while the bottom one shows their sum for different H^\pm masses at $\tan\beta = 40$. The signal peaks are clearly visible in the latter. One gets similar results for $\tan\beta = 1.5$.

Tab. 1 lists the number of signal and background events over a 80 GeV bin around the H^\pm mass for an annual luminosity of 100 fb^{-1} , expected from the high luminosity run of the LHC. The corresponding values of S/\sqrt{B} are also shown. We see a better than $5(3)\sigma$ signal up to a H^\pm mass of 400(600) GeV at $\tan\beta = 40$. It may be noted that both the signal size and the S/\sqrt{B} ratio are better here in comparison with the 4 b -tagged channel [4] for $\epsilon_b = 40\%$ and p_T cut of 30 GeV. But the S/B ratio is better in the latter case. Similar results hold for $\tan\beta = 1.5$.

In summary, the isolated lepton + multi-jet channel with triple b -tagging – supplemented by a transverse momentum cut on the third b -jet – offers a promising signature for H^\pm searches at the LHC up to $M_{H^\pm} \approx 600$ GeV at $\tan\beta \gtrsim 40$ and $\lesssim 1.5$, thus extending the reach of previous similar analyses [2,3]. Hence it calls for a more detailed study, including hadronisation, jet identification and detector effects.

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Number of events per year			
$M_{H^\pm} \pm 40 \text{ GeV}$	S	B	S/\sqrt{B}
310	133	443	6.2
407	111	403	5.6
506	73	266	4.5
605	43	156	3.4
MRS-LO [$Q = \mu = m_t + M_{H^\pm}$]			
$3b + n \text{ jets} + \ell^\pm + p_{\text{miss}}^T$ (with $n = 2, 3$)			After all cuts

Table 1: Number of events from the signal (2)–(3), S , and the sum of the backgrounds (10)–(12), B , along with the statistical significance, S/\sqrt{B} , per 100 inverse femtobarns of integrated luminosity, in a window of 80 GeV around four selected values of M_{H^\pm} (given in GeV) in the heavy mass range, for $\tan\beta = 40$. At least three b -jets are assumed to be tagged, each with efficiency $\epsilon_b = 40\%$, whereas the rejection factor against light jets is $\epsilon_{j=q,g} = 1\%$. All cuts discussed in the text, i.e. eqs. (15)–(16), steps (a)–(d) as well as the transverse momentum cut (17) on the b -jet accompanying the top-antitop pair, have been enforced. The PDF set used was MRS-LO(05A) with renormalisation and factorisation scales set equal to $m_t + M_{H^\pm}$.

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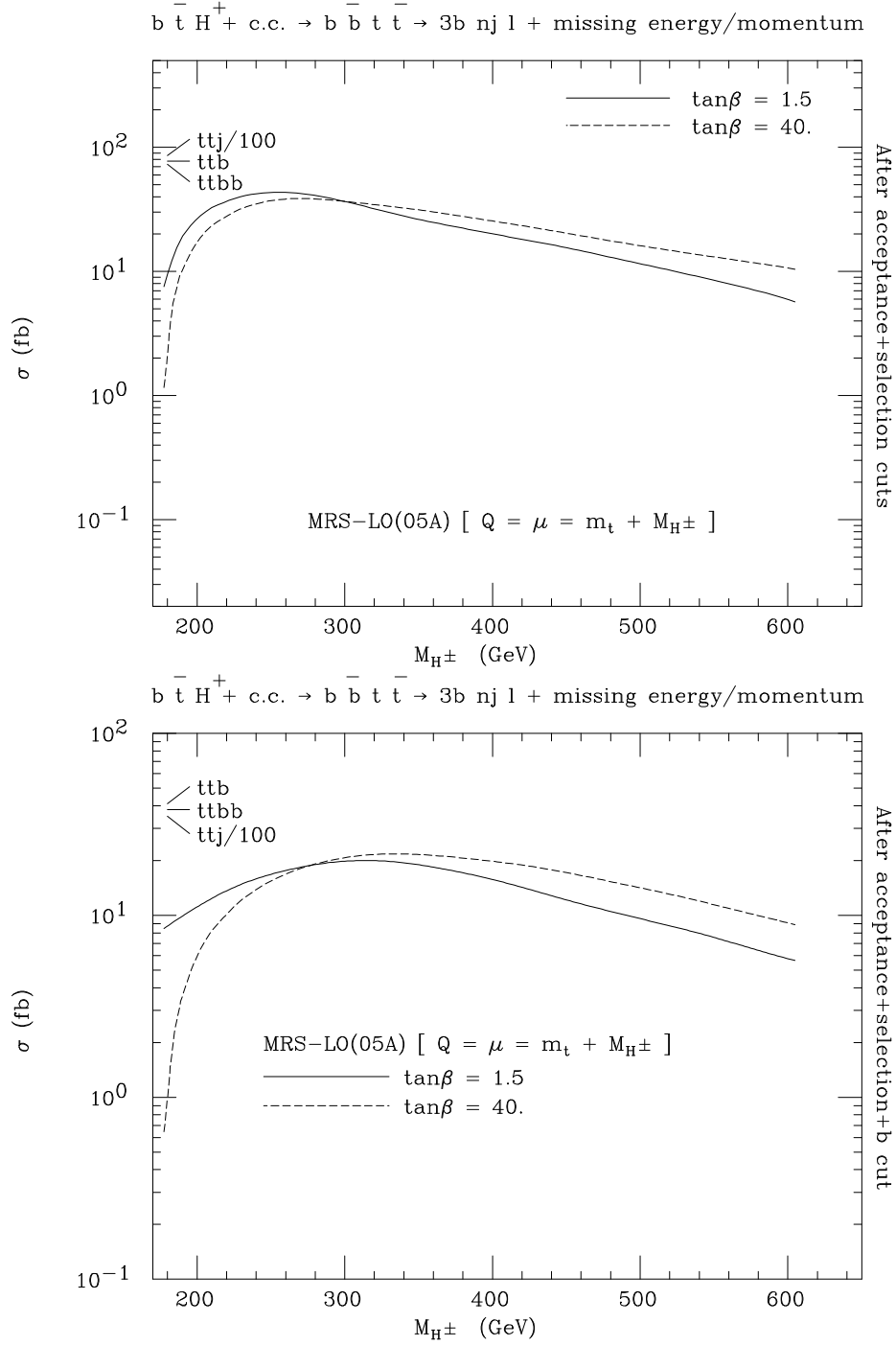


Figure 3: Production cross section for the signal (2)–(3) as a function of M_{H^\pm} in the heavy mass range, after the acceptance and selection cuts described in the text: i.e. eqs. (15)–(16) and steps (a)–(d) (top plot) as well as the transverse momentum cut (17) on the b -jet accompanying the top-antitop pair (bottom plot). The PDF set used was MRS-LO(05A) with renormalisation and factorisation scales set equal to $m_t + M_{H^\pm}$. The arrows represent the size of the backgrounds (10)–(12), the last of which has been divided by 100 (for readability). No b -tagging efficiency/rejection is included.

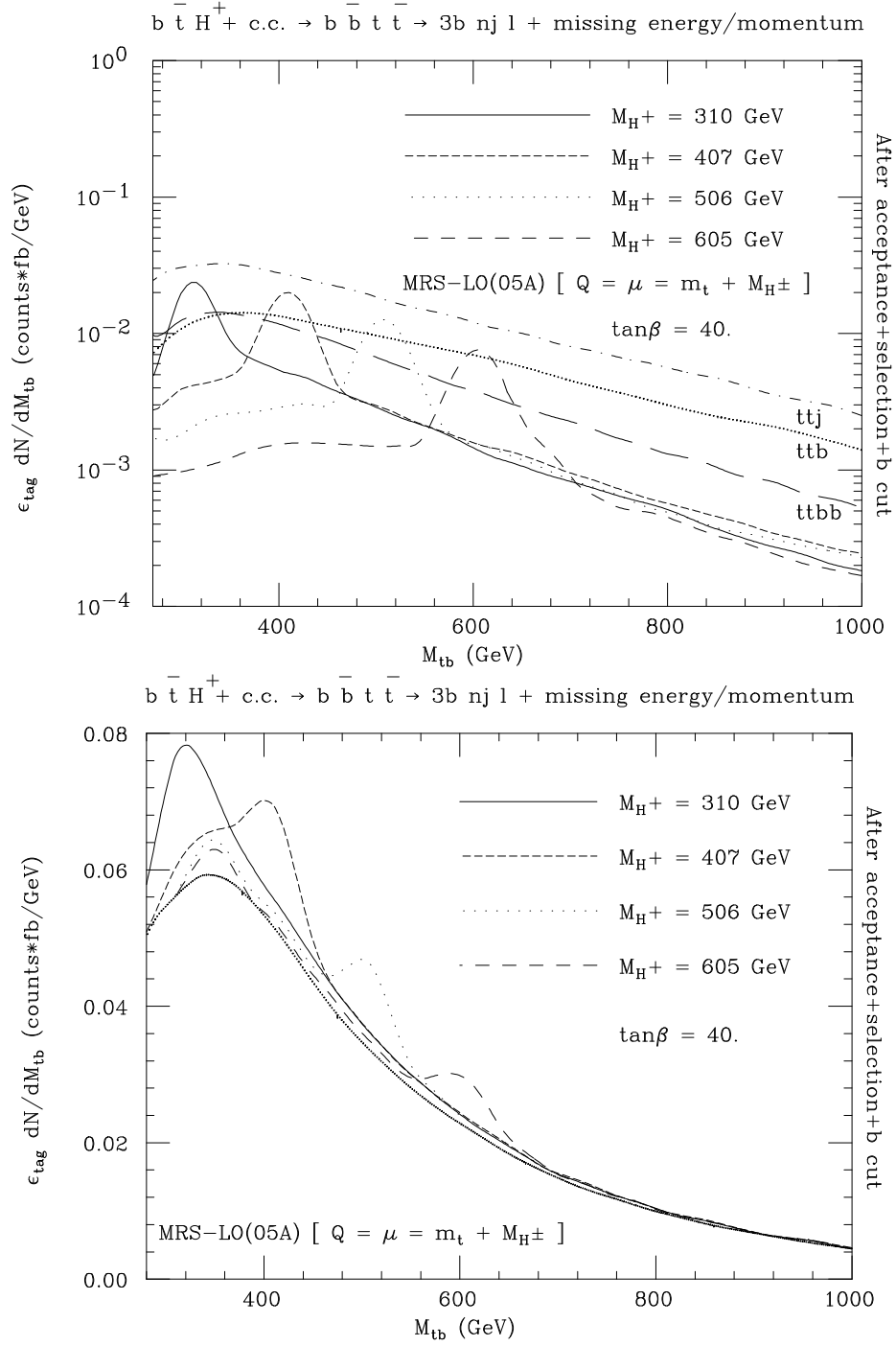


Figure 4: (Top plot) Differential distribution (two entries per each event generated) in the reconstructed charged Higgs mass for the signal (2)–(3), corresponding to four selected values of M_{H^\pm} in the heavy mass range, for $\tan\beta = 40$, after the acceptance and selection cuts described in the text: i.e. eqs. (15)–(16) and steps (a)–(d) as well as the transverse momentum cut (17) on the b -jet accompanying the top-antitop pair. The PDF set used was MRS-LO(05A) with renormalisation and factorisation scales set equal to $m_t + M_{H^\pm}$. The (fine-dotted)[long-dashed]{dot-dashed} curve represents the shape of the background process ((10))[(11)]{(12)}. (Bottom plot) As above, after summing each signal to all backgrounds. Tagging efficiencies have been included here, in both plots.